

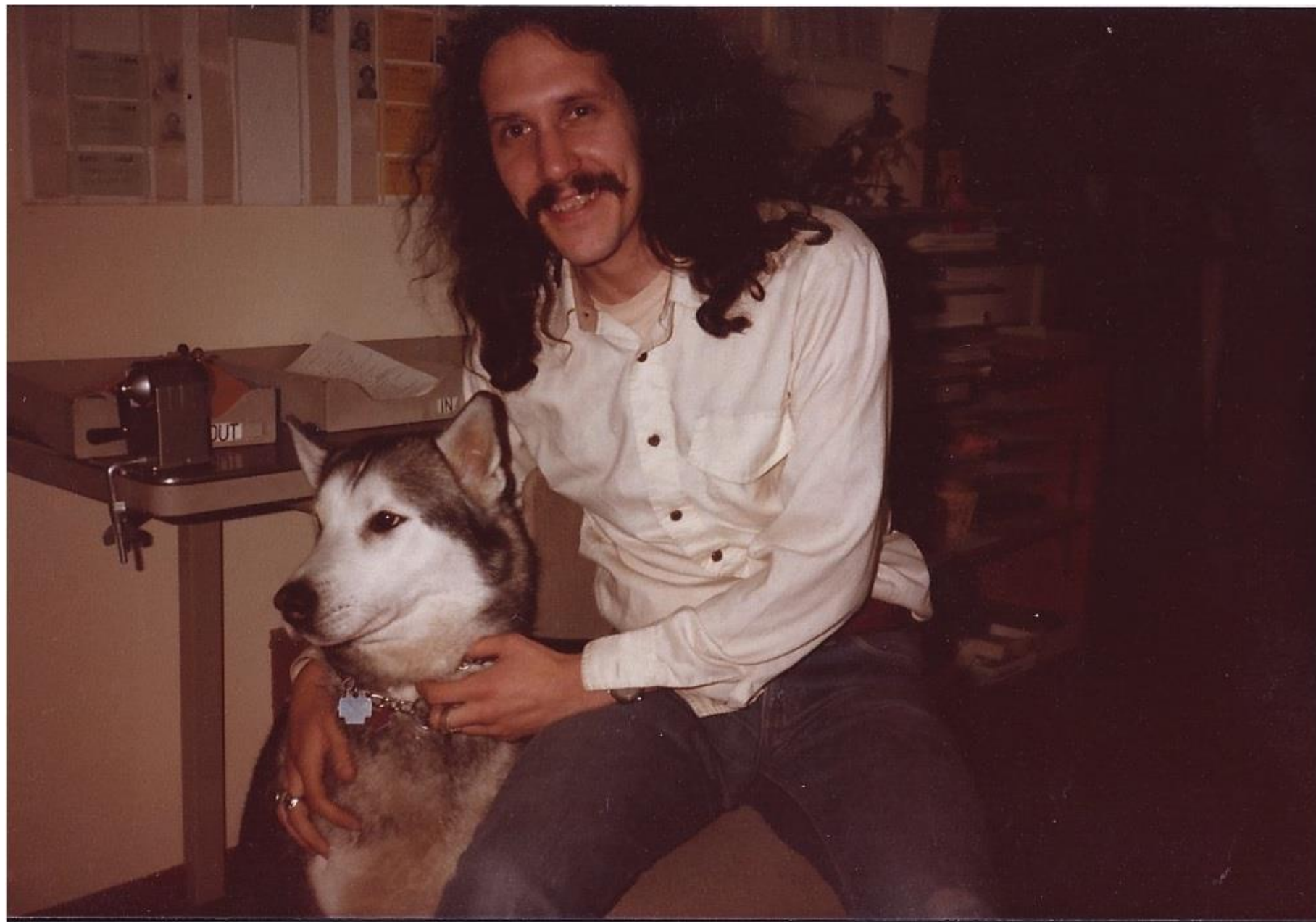


Dimitri Nanopoulos



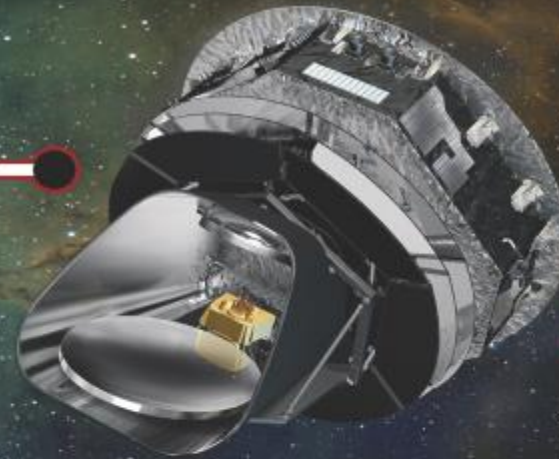
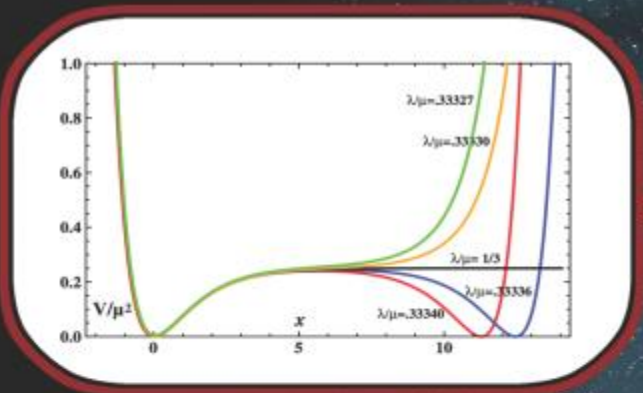
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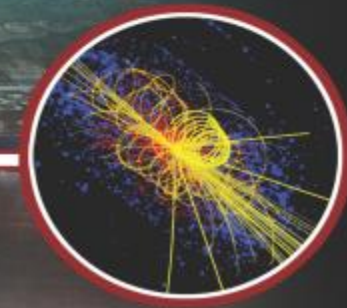
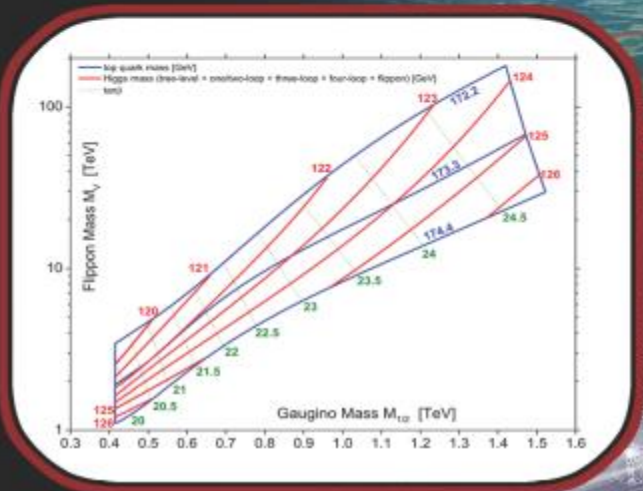
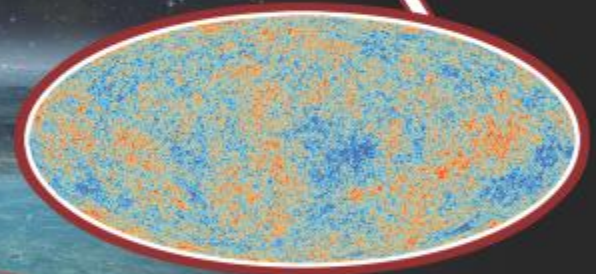






A NO-SCALE FRAMEWORK FOR SUBPLANCKIAN PHYSICS

DIMITRI V. NANOPOULOS

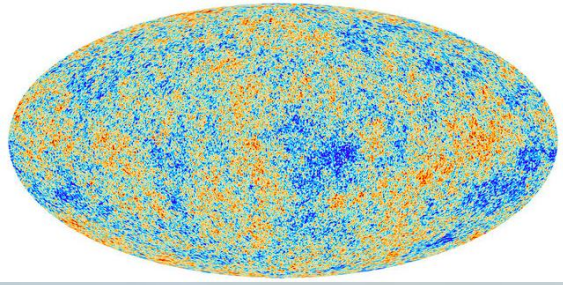


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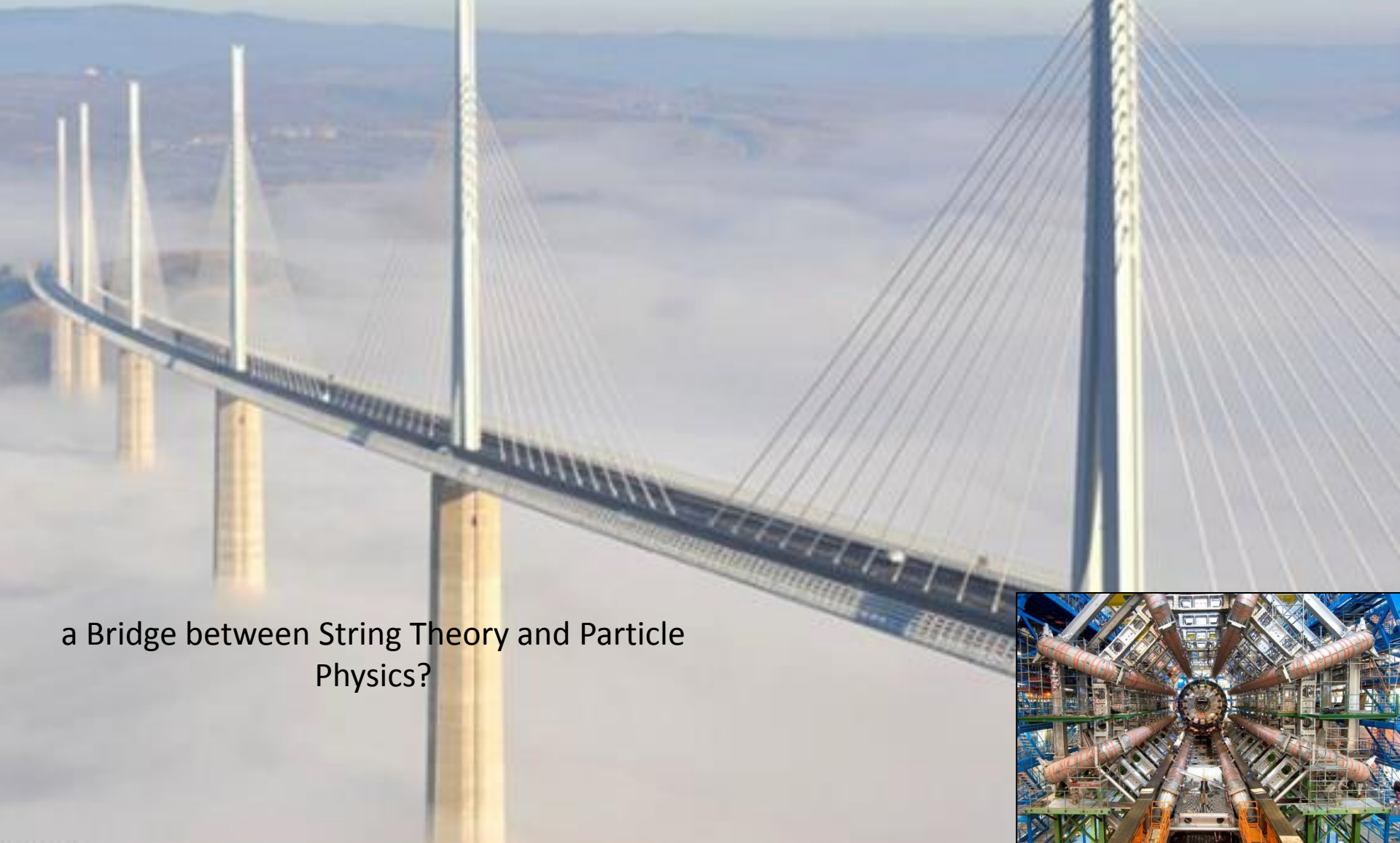


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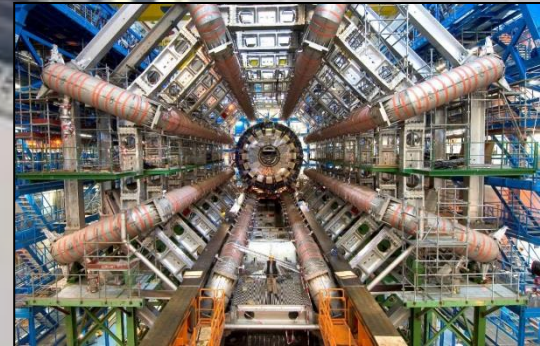




Flipped No-Scale Inflation



a Bridge between String Theory and Particle
Physics?



CMB: Opportunity & Challenge

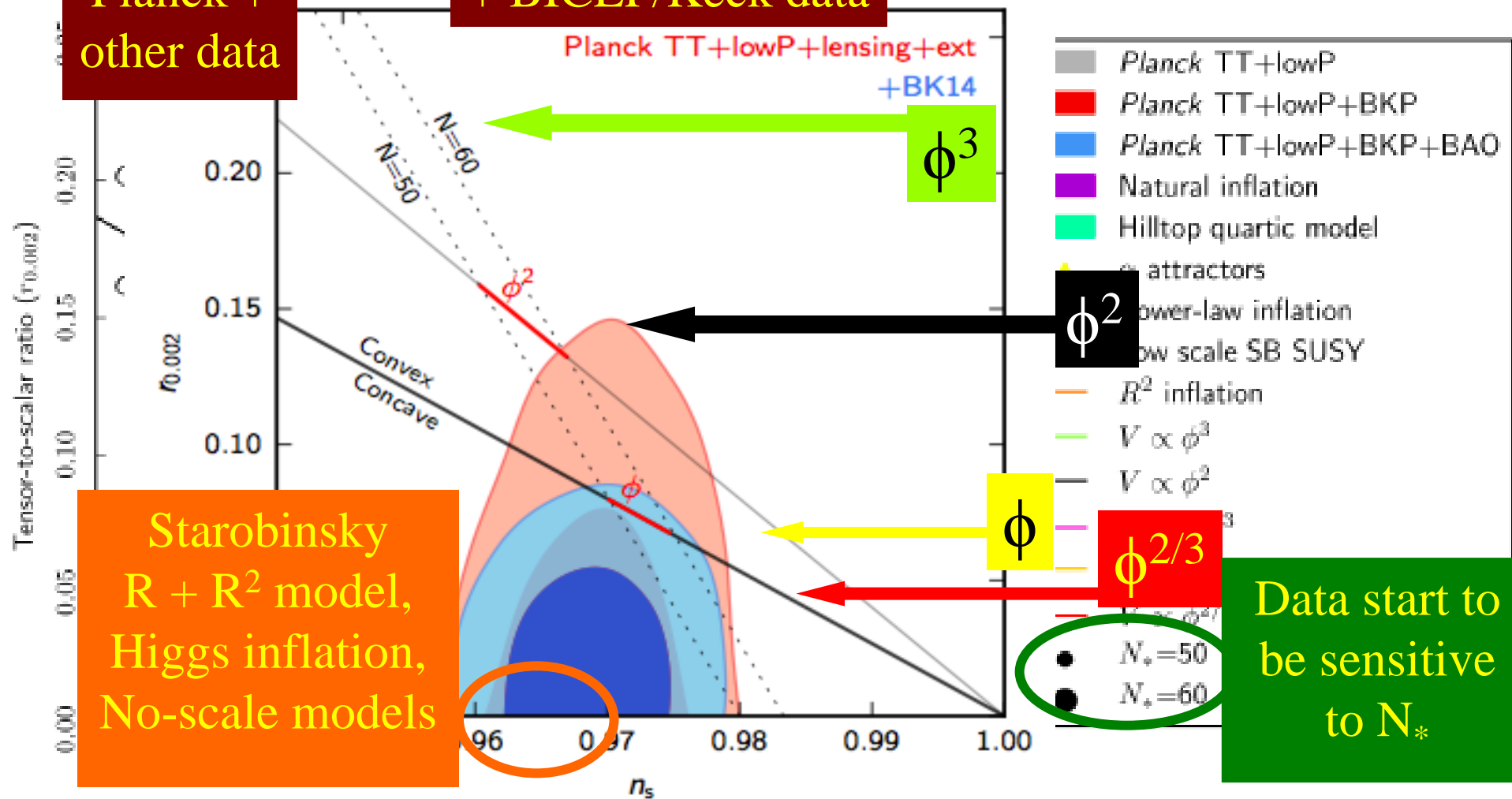
- Unique probe of (very) high-energy scale
- Close to string scale?
- Detailed measurements
 - ➔ Many probes of models of inflation
- Connection with collider physics via pattern of inflaton decay?
- Use string-motivated framework to construct models of inflation
- **No-scale supergravity × flipped unification**

Inflationary Landscape

Monomial Single-field potentials

Planck + other data

+ BICEP/Keck data



Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):

$$S = \frac{1}{2} \int d^4x \sqrt{-g} (R + R^2/6M^2)$$

Starobinsky, 1980

- **No scalar!?**

- **Conformally equivalent to scalar field model:**

$$S = \frac{1}{2} \int d^4x \sqrt{-\tilde{g}} \left[\tilde{R} + (\partial_\mu \varphi')^2 - \frac{3}{2} M^2 (1 - e^{-\sqrt{2/3} \varphi'})^2 \right]$$

Stelle; Whitt, 1984

- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2} \int d^4x \left[\dot{\phi}^2 - \nabla_a \phi \nabla^a \phi + \left(\frac{a''}{a} + M^2 a^2 \right) \phi^2 \right]$$

Inflation Cries out for Supersymmetry

- Want “elementary” scalar field
(at least looks elementary at energies $\ll M_P$)
- To get right magnitude of perturbations
prefer mass $\ll M_P$
($\sim 10^{13}$ GeV in simple ϕ^2 models)
- And/or prefer small self-coupling $\lambda \ll 1$
- **Both technically natural with supersymmetry**

No-Scale Supergravity Inflation

- **Supersymmetry + gravity = Supergravity**
- Include conventional matter?
- Potentials in generic supergravity models have ‘holes’ with depths $\sim -M_P^4$
- Exception: **no-scale supergravity**
Cremmer, Ferrara, Kounnas & Nanopoulos, 1983
- **Appears in compactifications of string**
Witten, 1985
- Flat directions, scalar potential \sim global model + controlled corrections
JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

No Scale SUGRA: A Case Study in Reductionism

There is a function called the Kähler potential which must be specified by the model builder in order to fix the metric of superspace, and determine the scalar potential. It is not fixed by the symmetries of the theory. There is however a particularly natural choice.

$$K = -3 \ln (T + T^* - \Sigma \phi_i^* \phi_i)$$



$$V_{SUGRA} = 0$$

The scalar potential is flat and vanishing. Supersymmetry is **BROKEN**, and there is no cosmological constant. This is all desirable at the *Tree Level*.

CONSTRAINT: $m_0 = 0, \quad A = 0, \quad B = 0 \quad m_{1/2} \neq 0$ for SUSY breaking

The gaugino mass $m_{1/2}$ remains undetermined at the classical level.

All soft-terms though, are dynamically evolved in terms of only the single parameter ($m_{1/2}$), which may itself be determined by radiative corrections to the potential !

- E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, Phys. Lett. B 133, 61 (1983)
J. R. Ellis, A. B. Lahanas, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B 134, 429 (1984)
J. R. Ellis, C. Kounnas and D. V. Nanopoulos, Nucl. Phys. B 241, 406 (1984)
A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. 145, 1 (1987)

No-Scale Supergravity

Natural vanishing of cosmological constant (tree level)
with the supersymmetry scale not fixed at lowest order.
(Also arises in generic 4d reductions of string theory.)

$$K = -3 \ln(T + T^* - \phi^i \phi_i^* / 3)$$

$$V = e^{\frac{2}{3}K} \left| \frac{\partial W}{\partial \phi^i} \right|^2$$

Globally supersymmetric potential once
K (canonical) picks up a vev

Old No-Scale Supergravity Model of Inflation

Volume 152B, number 3,4

PHYSICS LETTERS

8 March 1984

SU(N , 1) INFLATION

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Received 7 December 1984

We present a simple model for primordial inflation in the context of SU(N , 1) no-scale $n = 1$ supergravity. Because the model at zero temperature very closely resembles global supersymmetry, minima with negative cosmological constants do not exist, and it is easy to have a long inflationary epoch while keeping density perturbations of the right magnitude and satisfying other cosmological constraints. We pay specific attention to satisfying the thermal constraint for inflation, i.e. the existence of a high temperature minimum at the origin.

- No ‘holes’ in effective potential with negative cosmological constant

JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

No-Scale models revisited

Can we find a model consistent with Planck?

Ellis, Nanopoulos, Olive

Start with WZ model: $W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$

Assume now that T picks up a vev: $2\langle \text{Re } T \rangle = c$

$$\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2} |\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$$

Redefine inflaton to a canonical field χ

$$\hat{V} = |W_\Phi|^2$$

$$\phi = \sqrt{3c} \tanh\left(\frac{\chi}{\sqrt{3}}\right)$$

No-Scale models revisited

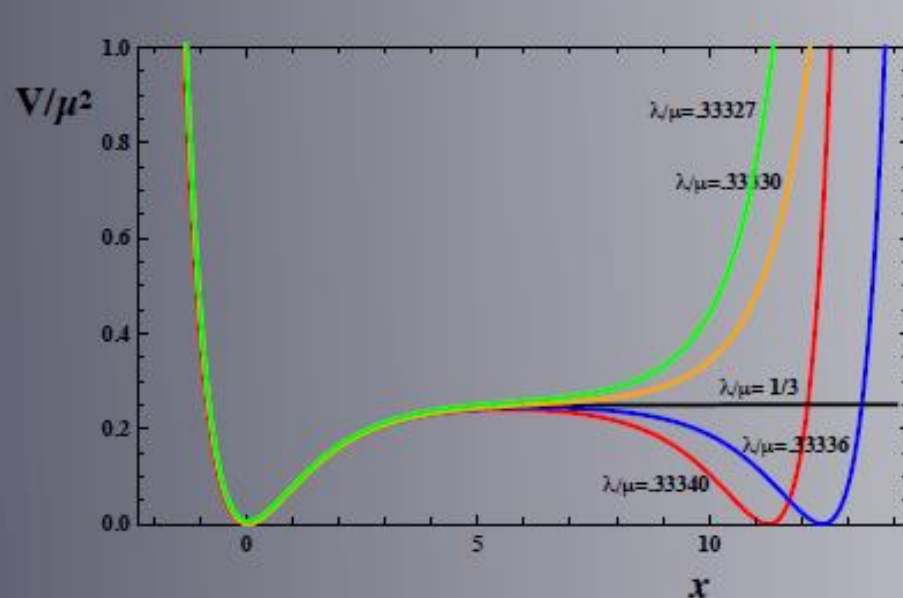
The potential becomes:

$$V = \mu^2 \left| \sinh(\chi/\sqrt{3}) \left(\cosh(\chi/\sqrt{3}) - \frac{3\lambda}{\mu} \sinh(\chi/\sqrt{3}) \right) \right|^2$$

$$\hat{\mu} = \mu \sqrt{c/3}$$

For $\lambda = \mu/3$, this is exactly the $R + R^2$ potential

$$V = \mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$$



$$\chi = (x + iy)/\sqrt{2}$$

No-Scale models revisited

The potential becomes:

$$V = \mu^2 \left| \sinh(\chi/\sqrt{3}) \left(\cosh(\chi/\sqrt{3}) - \frac{3\lambda}{\mu} \sinh(\chi/\sqrt{3}) \right) \right|^2$$

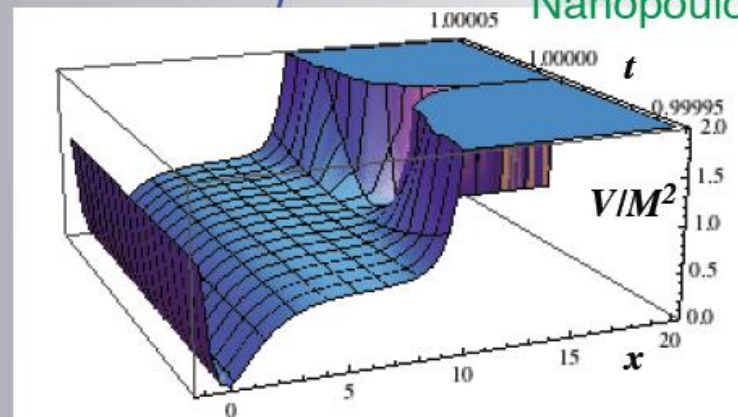
For $\lambda = \mu/3$, this is exactly the $R + R^2$ potential
and Starobinsky model of inflation

$$V = \mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$$

Have so far *assumed* a vev for one of the two fields

$$K = -3 \ln \left(T + T^* - \frac{|\phi|^2}{3} + \frac{(T + T^* - 1)^4 + d(T - T^*)^4}{\Lambda^2} \right)$$

Ellis, Kounnas,
Nanopoulos



How many e-Folds of Inflation?

- General expression:

JE, García, Nanopoulos & Olive, arXiv:1505.06986

$$N_* = 67 - \ln \left(\frac{k_*}{a_0 H_0} \right) + \frac{1}{4} \ln \left(\frac{V_*^2}{M_P^4 \rho_{\text{end}}} \right) + \frac{1 - 3w_{\text{int}}}{12(1 + w_{\text{int}})} \ln \left(\frac{\rho_{\text{reh}}}{\rho_{\text{end}}} \right) - \frac{1}{12} \ln g_{\text{th}}$$

- In no-scale supergravity models:

$$N_* = 68.659 - \ln \left(\frac{k_*}{a_0 H_0} \right) + \frac{1}{4} \ln (A_{S*}) - \frac{1}{4} \ln \left(N_* - \sqrt{\frac{3}{8}} \frac{\phi_{\text{end}}}{M_P} + \frac{3}{4} e^{\sqrt{\frac{2}{3}} \frac{\phi_{\text{end}}}{M_P}} \right) \\ + \frac{1 - 3w_{\text{int}}}{12(1 + w_{\text{int}})} (2.030 + 2 \ln (\Gamma_\phi / m) - 2 \ln (1 + w_{\text{eff}}) - 2 \ln (0.81 - 1.10 \ln \delta)) \\ - \frac{1}{12} \ln g_{\text{th}}$$

Amplitude of perturbations

Equation of state during inflaton decay

Inflaton decay rate

- Prospective constraint on inflaton models?

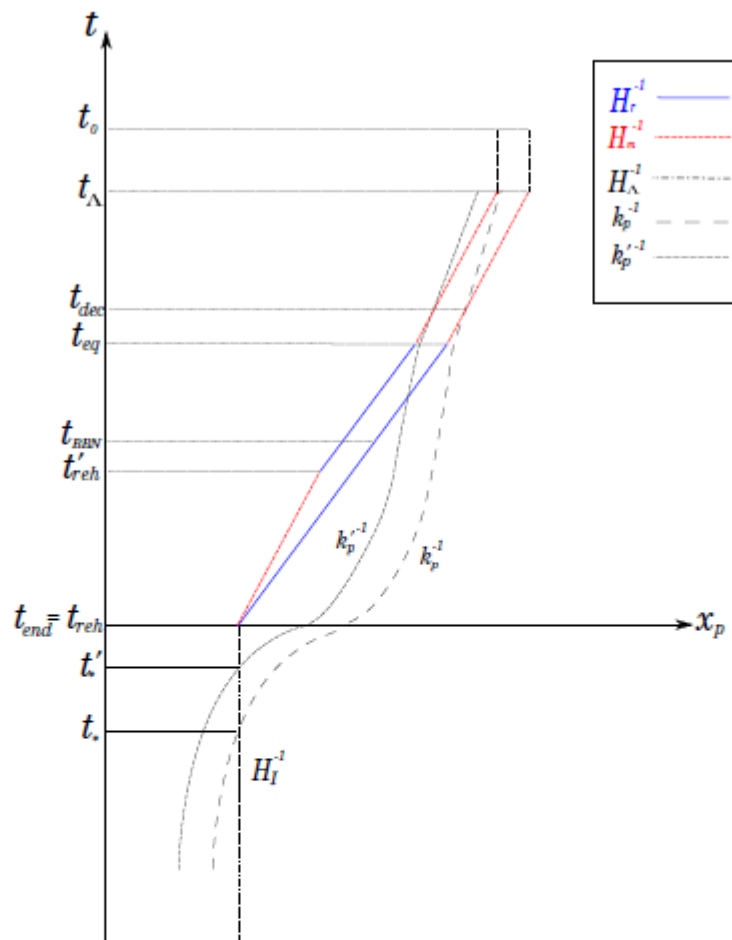
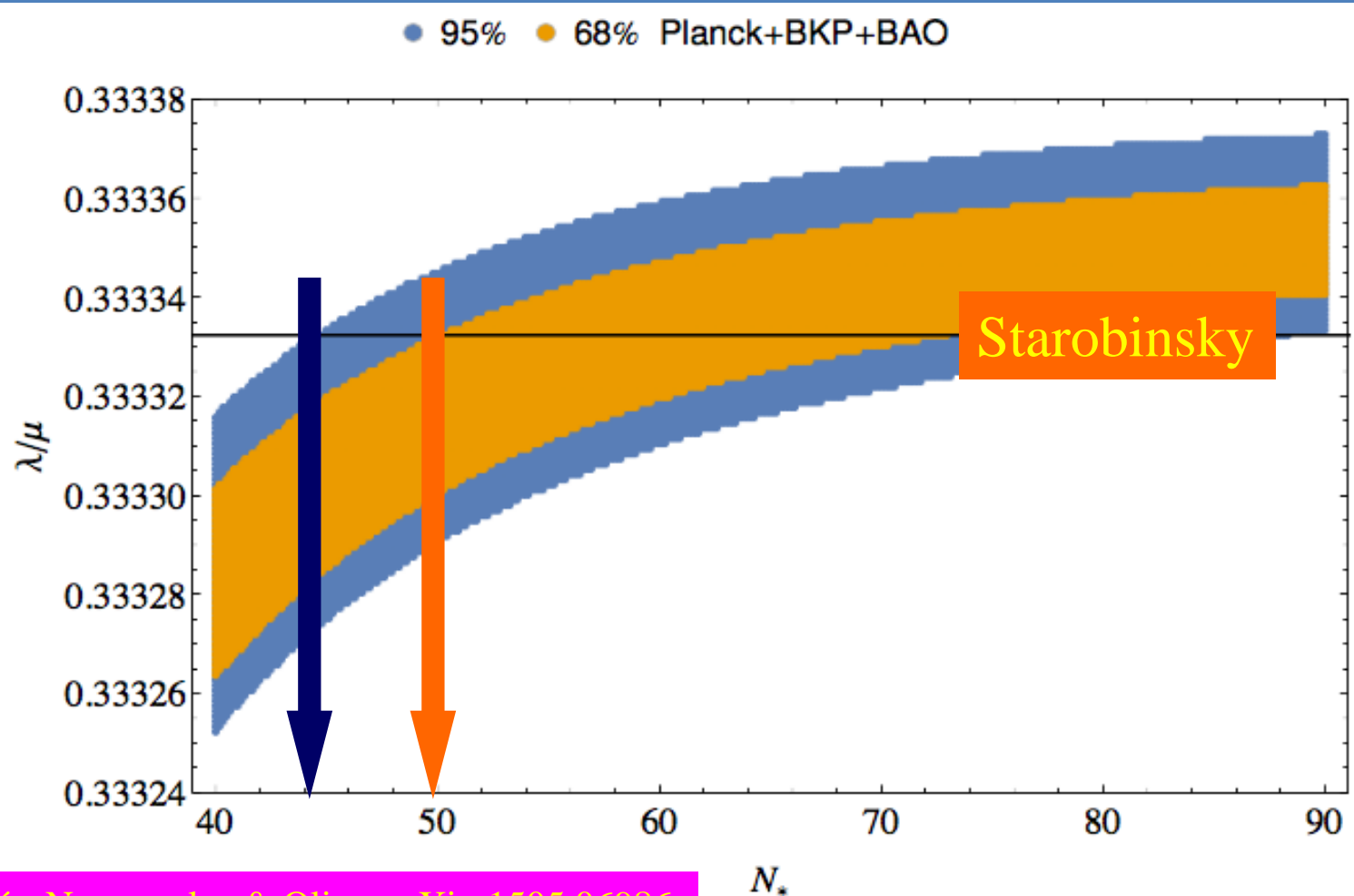
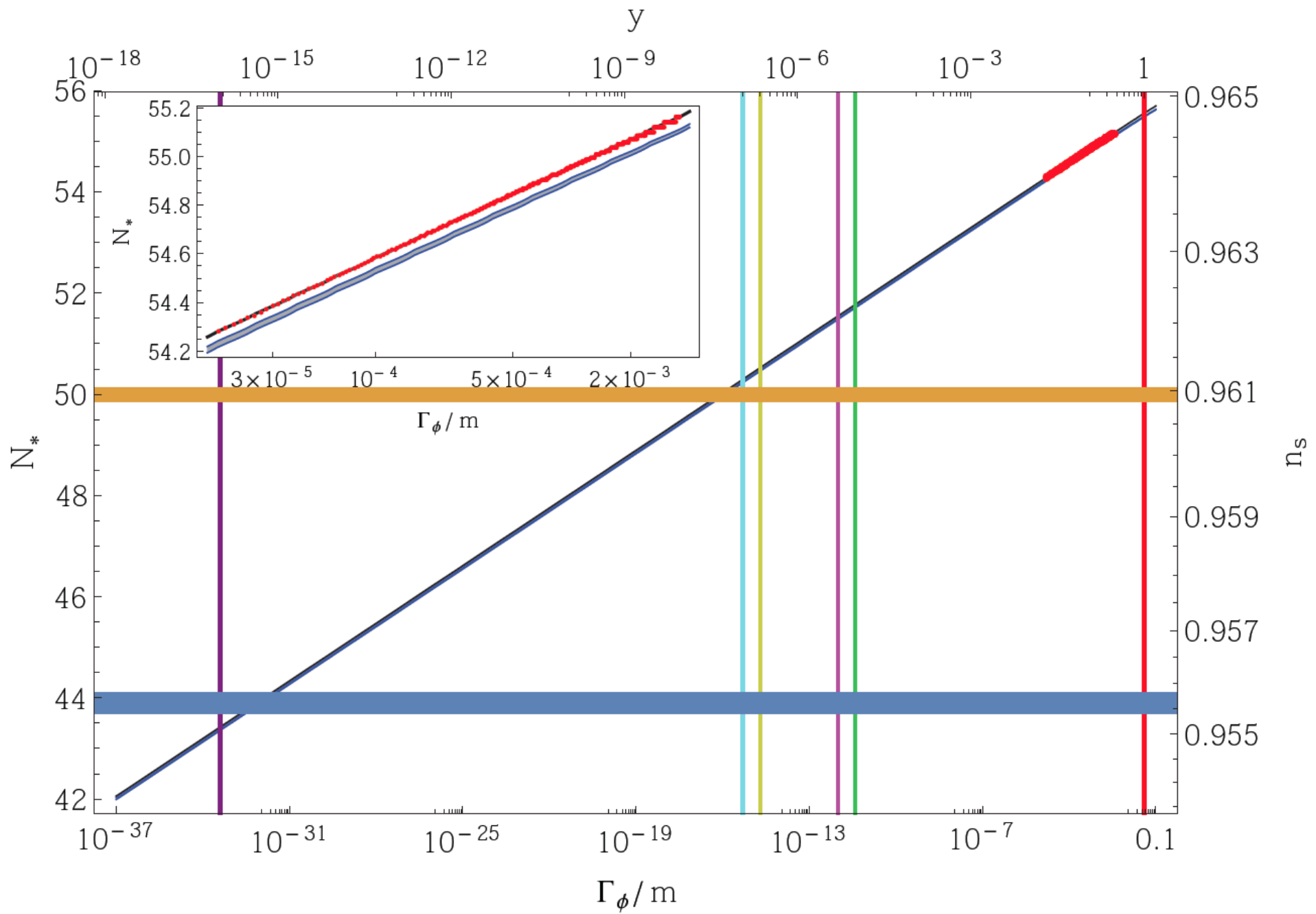


Figure 2: Evolution of physical wavelengths as labelled by their inverse wavenumber k_p^{-1} during inflation (below the x-axis) and during the post-inflationary epoch (above the x-axis). The solid (blue) line represents the Hubble radius, H_r^{-1} in a Universe dominated by a radiation fluid $w = 1/3$, the dashed (red) line is the Hubble radius, H_m^{-1} in a post-inflationary era dominated by a pressureless fluid, $w = 0$. We compare the evolution of a physical mode k_* that re-enters at CMB decoupling in the standard scenario (Radiation \rightarrow Matter \rightarrow Dark energy) with a mode k'_* that re-enters at CMB decoupling in the nonthermal scenario (Matter \rightarrow Radiation \rightarrow Matter \rightarrow Dark Energy). These modes exit the Hubble radius at different times during inflation, t_* and t'_* , which translates into a shift in the number of e-folds $\Delta N = H \Delta t$. The corresponding shift in the pivot scale or any co-moving mode is given by $k'_* = k_* e^{-\Delta N}$.

Planck Constraints on # of e-Folds

- Starobinsky-like no-scale models





Starobinsky-like Inflation, Supercosmology and Neutrino Masses in No-Scale Flipped SU(5)

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ABSTRACT

We embed a flipped $SU(5) \times U(1)$ GUT model in a no-scale supergravity framework, and discuss its predictions for cosmic microwave background observables, which are similar to those of the Starobinsky model of inflation. Measurements of the tilt in the spectrum of scalar perturbations in the cosmic microwave background, n_s , constrain significantly the model parameters. We also discuss the model's predictions for neutrino masses, and pay particular attention to the behaviours of scalar fields during and after inflation, reheating and the GUT phase transition. We argue in favor of strong reheating in order to avoid excessive entropy production which could dilute the generated baryon asymmetry.

April 2017

Flipped

Almost

A Model of Everything

Below the Planck Scale

- Simple GUT models ($SU(5)$, $SO(10)$) not obtained from weakly-coupled string
 - They need adjoint Higgs, ...
- **Flipped $SU(5) \times U(1)$ derived**, has advantages
 - Small (5-, 10-dimensional) Higgs representations
 - Long-lived proton, neutrino masses, leptogenesis, ...
- Construct model of Starobinsky-like inflation within flipped $SU(5) \times U(1)$ framework

Flipped SU(5)×U(1) GUT Model

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Fields:

$F_i = (\mathbf{10}, 1)_i \quad \ni \{d^c, Q, \nu^c\}_i$ – Matter: $\bar{f}_i = (\bar{\mathbf{5}}, -3)_i \quad \ni \{u^c, L\}_i$, $\ell_i^c = (\mathbf{1}, 5)_i \quad \ni \{e^c\}_i$, – Singlets: $\phi_a = (\mathbf{1}, 0), a = 0, \dots, 3$	Higgs: $H = (\mathbf{10}, 1)$, $\bar{H} = (\bar{\mathbf{10}}, -1)$, $h = (\mathbf{5}, -2)$, $\bar{h} = (\bar{\mathbf{5}}, 2)$,
--	---
- Superpotential:

$$W = \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{f}_j \bar{h} + \lambda_3^{ij} \bar{f}_i \ell_j^c h + \lambda_4 H H h + \lambda_5 \bar{H} \bar{H} \bar{h} + \lambda_6^{ia} F_i \bar{H} \phi_a + \lambda_7^a h \bar{h} \phi_a + \lambda_8^{abc} \phi_a \phi_b \phi_c + \mu^{ab} \phi_a \phi_b,$$
- No-scale Kähler potential:

$$K = -3 \ln \left[T + \bar{T} - \frac{1}{3} (|\phi_a|^2 + |\ell^c|^2 + f^\dagger f + h^\dagger h + \bar{h}^\dagger \bar{h} + F^\dagger F + H^\dagger H + \bar{H}^\dagger \bar{H}) \right]$$
- D-terms: $D^a D^a = \left(\frac{3}{10} g_5^2 + \frac{1}{80} g_X^2 \right) (|\tilde{\nu}_i^c|^2 + |\tilde{\nu}_H^c|^2 - |\tilde{\nu}_{\bar{H}}^c|^2)^2$
- Symmetry breaking: $SU(5) \times U(1) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$
- Proton lifetime: $\tau_p = 4.6 \times 10^{35} \times \left(\frac{M_{32}}{10^{16} \text{ GeV}} \right)^4 \times \left(\frac{0.0374}{\alpha_5(M_{32})} \right)^2 \text{ yrs}$

Starobinsky-Like Inflation

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Need superpotential: $W \supset m \left(\frac{S^2}{2} - \frac{S^3}{3\sqrt{3}} \right)$
- Identify inflaton S with some combination of Φ_a , consider 2 scenarios:
- **1) Hierarchy of scalars*** with one light eigenstate Φ_0^D :

$$\mu_D^{ab} = \text{diag} \left(m/2, \mu_D^{11}, \mu_D^{22}, \mu_D^{33} \right), \quad \mu_D^{ab} \leq M_{\text{GUT}} \quad : \quad \det \mu^{ab} \ll M_{\text{GUT}}^4$$

- “Starobinsky” condition: $-3\sqrt{3} \lambda_{8,D}^{000} = m$
- $$V_F \simeq \frac{3}{4} m^2 \left(1 - e^{-\sqrt{2/3} s} \right)^2 + \frac{3}{4} \sinh^2(\sqrt{2/3} s) \sum_i |\lambda_6^{i0}|^2 (|\tilde{\nu}_{\bar{H}}^c|^2 + |\tilde{\nu}_i^c|^2) + \frac{1}{8} m^2 e^{\sqrt{2/3} s} \left(|\tilde{\nu}_{\bar{H}}^c|^2 + \sum_i |\tilde{\nu}_i^c|^2 \right) + \dots$$

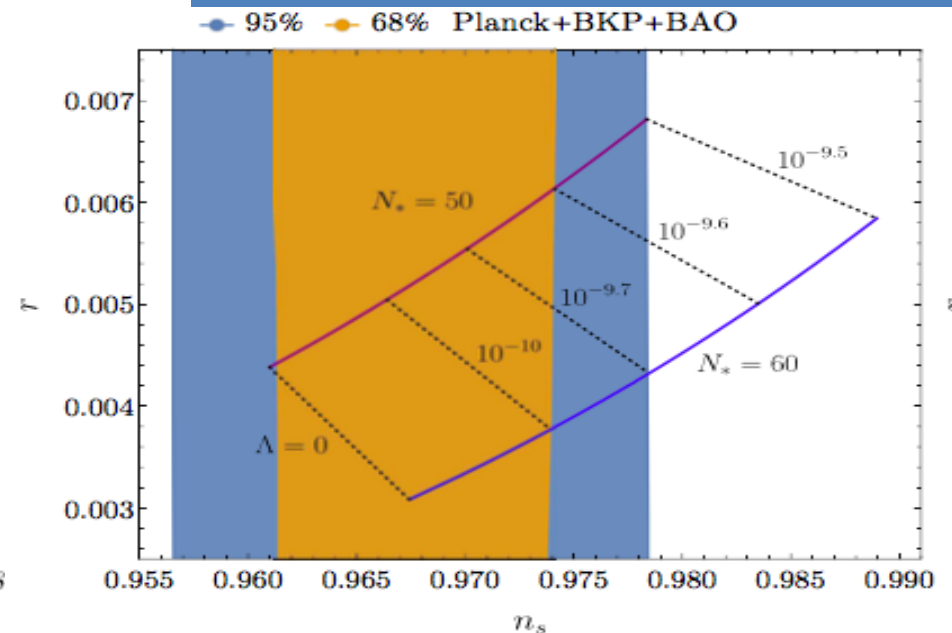
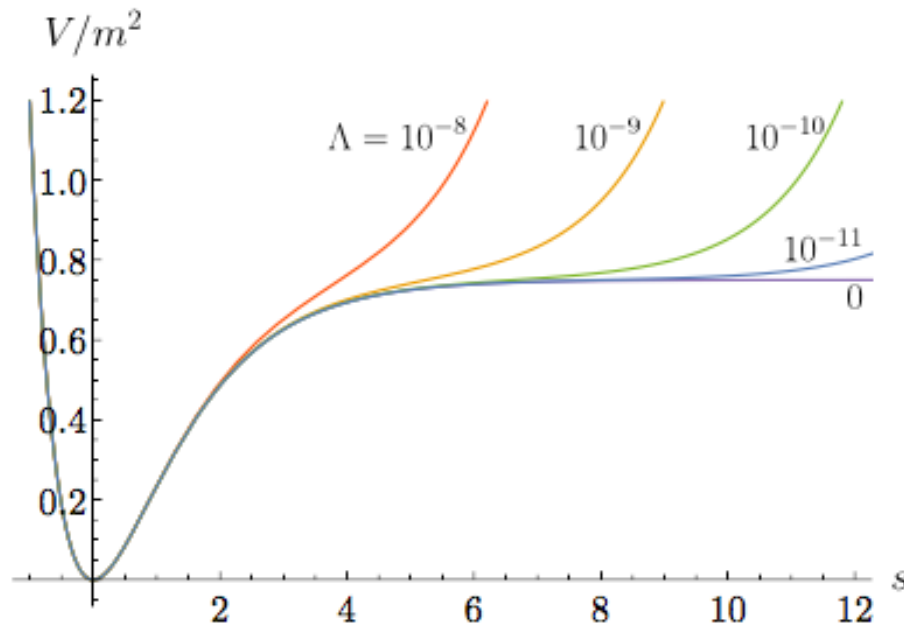
* Consider later scenario **2) no scalar mass hierarchy**

Starobinsky-Like Inflation in Scenario (1)

- Consider case of (relatively) large λ : $\lambda_8^{0ij} \gtrsim \mu^{ij}$

- Potential
$$\simeq \frac{3}{4}m^2 \left(1 - e^{-\sqrt{2/3}s}\right)^2 + \frac{27\sqrt{3}}{4}m\Lambda e^{-s/\sqrt{6}} \sinh^3(s/\sqrt{6})$$

- Where
$$\Lambda \equiv -\sum_{i,j} (\lambda_8^{0ij})^{-1} \lambda_8^{00i} \lambda_8^{00j} + \text{h.c.}$$



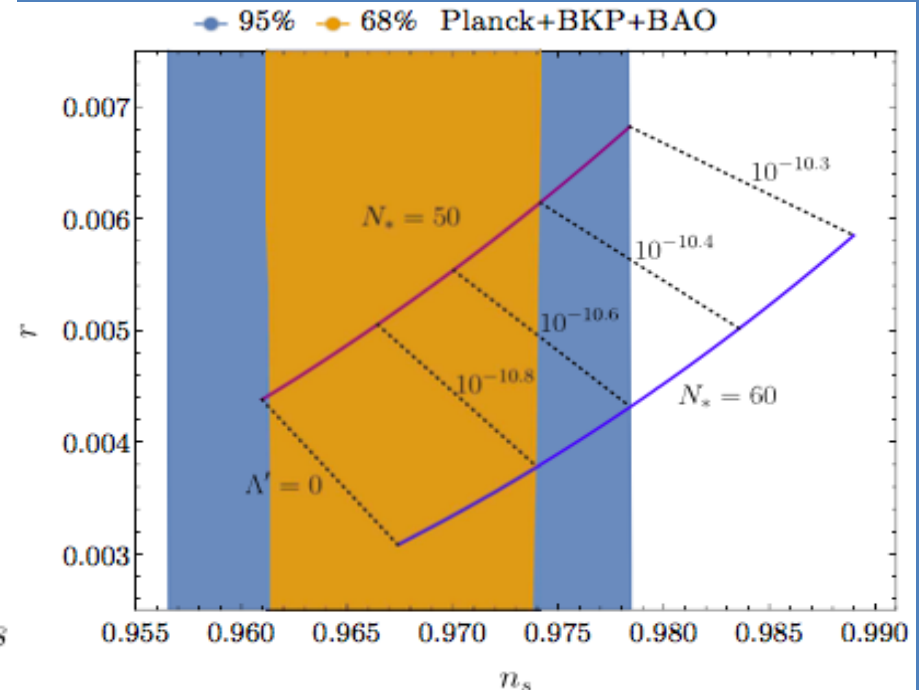
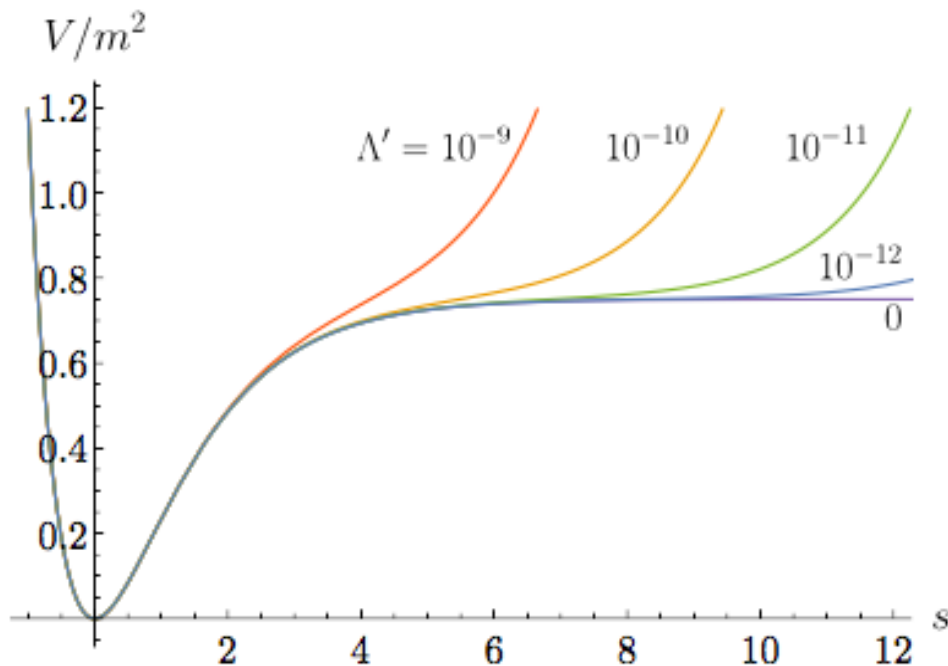
Starobinsky-Like Inflation in Scenario (1)

- Consider case of (relatively) small λ : $\lambda_8^{0ij} \lesssim \mu^{ij}$

$$V_{\text{inf}} \simeq \frac{3}{4} m^2 \left(1 - e^{-\sqrt{2/3}s}\right)^2 + 81 m \sinh^4(s/\sqrt{6}) \left(\tanh(s/\sqrt{6}) - 1\right) \sum_i [\mu_i^{-1} (\lambda_8^{00i})^2 + \text{h.c.}]$$

where

$$\Lambda' = - \sum_a \mu_a^{-1} (\lambda_8^{00a})^2 + \text{h.c.}$$

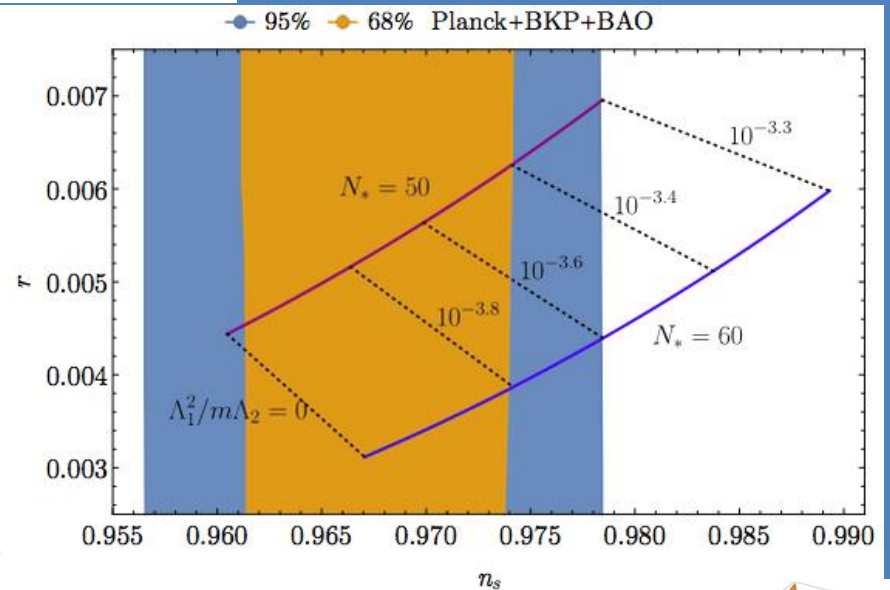
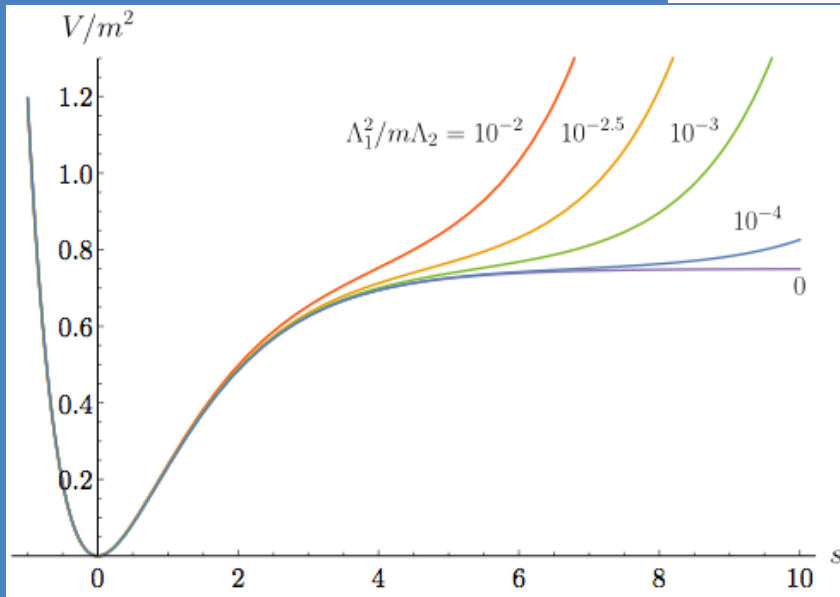


Starobinsky-Like Inflation in Scenario (2)

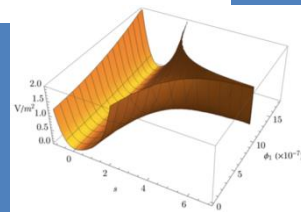
- Multiple light singlet states: correction to Starobinsky potential:

$$\Delta V_{\text{inf}} \sim \frac{\sqrt{3} m \sinh(\sqrt{2/3} s)}{2(1 + \tanh(s/\sqrt{6}))} \frac{\Lambda_1^2}{\Lambda_2} \sim m \frac{\sqrt{3} \Lambda_1^2}{8 \Lambda_2} e^{\sqrt{2/3} s}$$

where $\lambda_8^{00i} S \sim \mu^{0i} \sim \Lambda_1$ $\lambda_8^{0ij} S \sim \mu^{ij} \sim \Lambda_2$

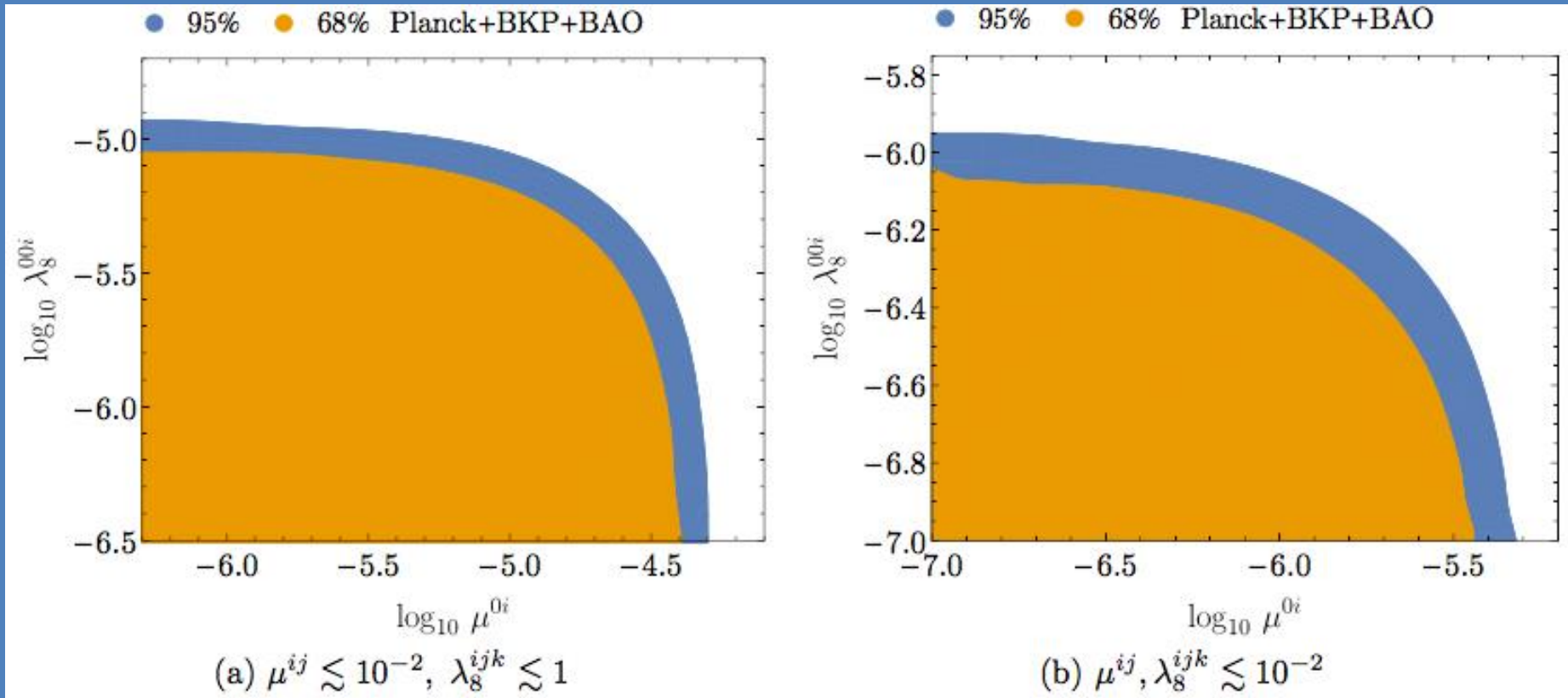


- Multi-field effects not a problem, steep valley:



Full Numerical Calculations

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331



- Constraints including numerical calculations of evolution of inflaton and other scalar fields

Neutrino Masses & Mixing

- Consider 2 options:
- (A) Inflaton decouples from neutrinos
 - Inflaton decays to Higgs(inos): leptogenesis difficult
- (B) Inflaton couples to neutrinos

$$\mathcal{L}_{\text{mass}}^{(i')} = -\frac{1}{2} \begin{pmatrix} \nu_{i'} & \nu_{i'}^c & \tilde{S} \end{pmatrix} \begin{pmatrix} 0 & \lambda_2^{i'i'} \langle \bar{h}_0 \rangle & 0 \\ \lambda_2^{i'i'} \langle \bar{h}_0 \rangle & 0 & \lambda_6^{i'0} \langle \tilde{\nu}_{\bar{H}}^c \rangle \\ 0 & \lambda_6^{i'0} \langle \tilde{\nu}_{\bar{H}}^c \rangle & m \end{pmatrix} \begin{pmatrix} \nu_{i'} \\ \nu_{i'}^c \\ \tilde{S} \end{pmatrix} + \text{h.c.}$$

- Double seesaw mass matrix, 2 heavy states, couplings

$$W = \lambda_2^{i'j} (\cos \theta N_{i'1} - \sin \theta N_{i'2}) L_j h_u \quad \text{where} \quad \tan 2\theta = -\frac{2\lambda_6^{i'0} \langle \tilde{\nu}_{\bar{H}}^c \rangle}{m}$$

- Constraints from neutrino data, easier leptogenesis

Neutrino Masses & Inflaton Coupling

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- To avoid overproduction of dark matter via gravitinos if no later entropy

$$|y| < 2.7 \times 10^{-5} \left(1 + 0.56 \frac{m_{1/2}^2}{m_{3/2}^2} \right)^{-1} \left(\frac{100 \text{ GeV}}{m_{\text{LSP}}} \right)$$

- With entropy factor Δ , if inflaton couples to neutrinos:

$$|\lambda_2^{i'j} \sin \theta| \lesssim 10^{-5} \Delta$$

- Normal neutrino mass hierarchy preferred

$$m_{\nu_1} \simeq 10^{-9} \times \left(\frac{|\lambda_6^{10}|}{10^{-3}} \right)^{-2} \left(\frac{|\langle \tilde{\nu}_H^c \rangle|}{10^{16} \text{ GeV}} \right)^{-2} \left(\frac{m}{3 \times 10^{13} \text{ GeV}} \right) \text{ eV}$$

$$m_{\nu_2} \simeq |\delta m^2|^{\frac{1}{2}} \simeq 9 \times 10^{-3} \text{ eV}$$

$$m_{\nu_3} \simeq |\Delta m^2|^{\frac{1}{2}} \simeq 5 \times 10^{-2} \text{ eV}$$

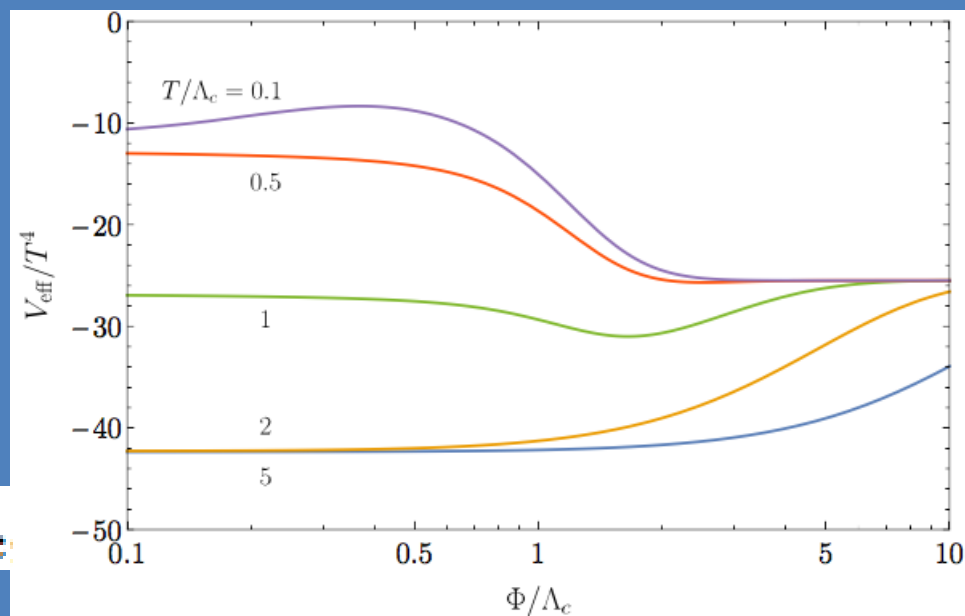
- Weak or strong reheating? Much much extra entropy?

The GUT Phase Transition

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- At the end of inflation, flipped $SU(5) \times U(1)$ unbroken
- At lower scales, α_5 increases, condensates form breaking $SU(5)$:

$$g^2(\Lambda_c) \Delta C \equiv g^2(\Lambda_c) (C_c - C_1 - C_2) \simeq 4, \quad \alpha_c \equiv \alpha(\Lambda_c) \simeq \frac{1}{\pi \Delta C}$$
- Typical condensation scale: $\Lambda_c \simeq 4 \times 10^{-7} M_{\text{GUT}} \simeq 5 \times 10^9 \text{ GeV}$
- Temperature-dependent effective potential
- Possibility of trapping at origin, excessive entropy release: avoid if $T_{\text{reh}} \gtrsim \Lambda_c$



Entropy Release & Baryogenesis

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Entropy release

$$\Delta \simeq 8 \times 10^3 \lambda_{1,2,3,7}^{-2} \left(\frac{g_{d\Phi}}{43/4} \right)^{1/4} \left(\frac{915/4}{g_{\text{dec}}} \right) \left(\frac{\langle \Phi \rangle}{5 \times 10^{15} \text{ GeV}} \right) \left(\frac{10 \text{ TeV}}{m_{F,\bar{f},\ell^c,\tilde{\phi}_a}^2 / |m_\Phi|} \right)^{1/2}$$

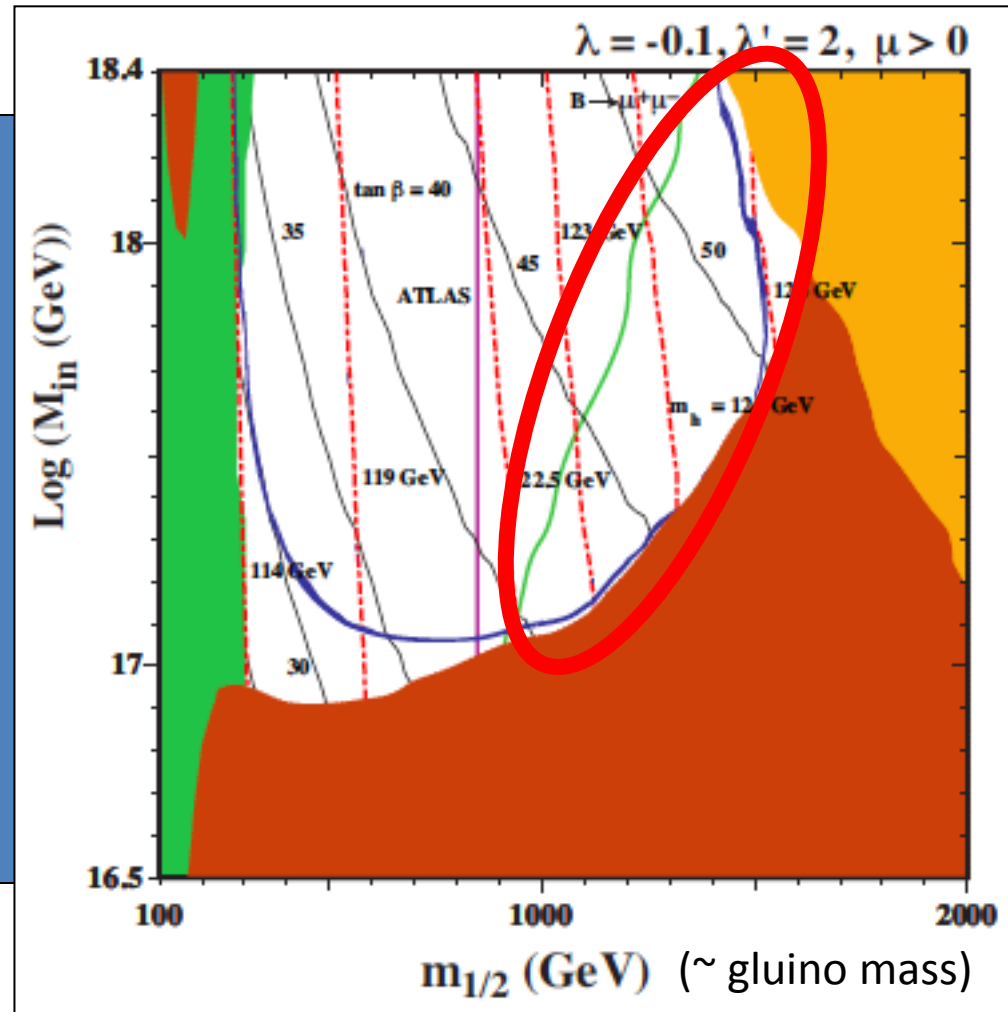
- Relaxes gravitino production constraint, little effect on number of inflationary e-folds: $\Delta N_*^{\text{max}} \simeq -4 \times 10^{-3} \ln \Delta$
- Standard leptogenesis if inflaton couples to neutrinos:

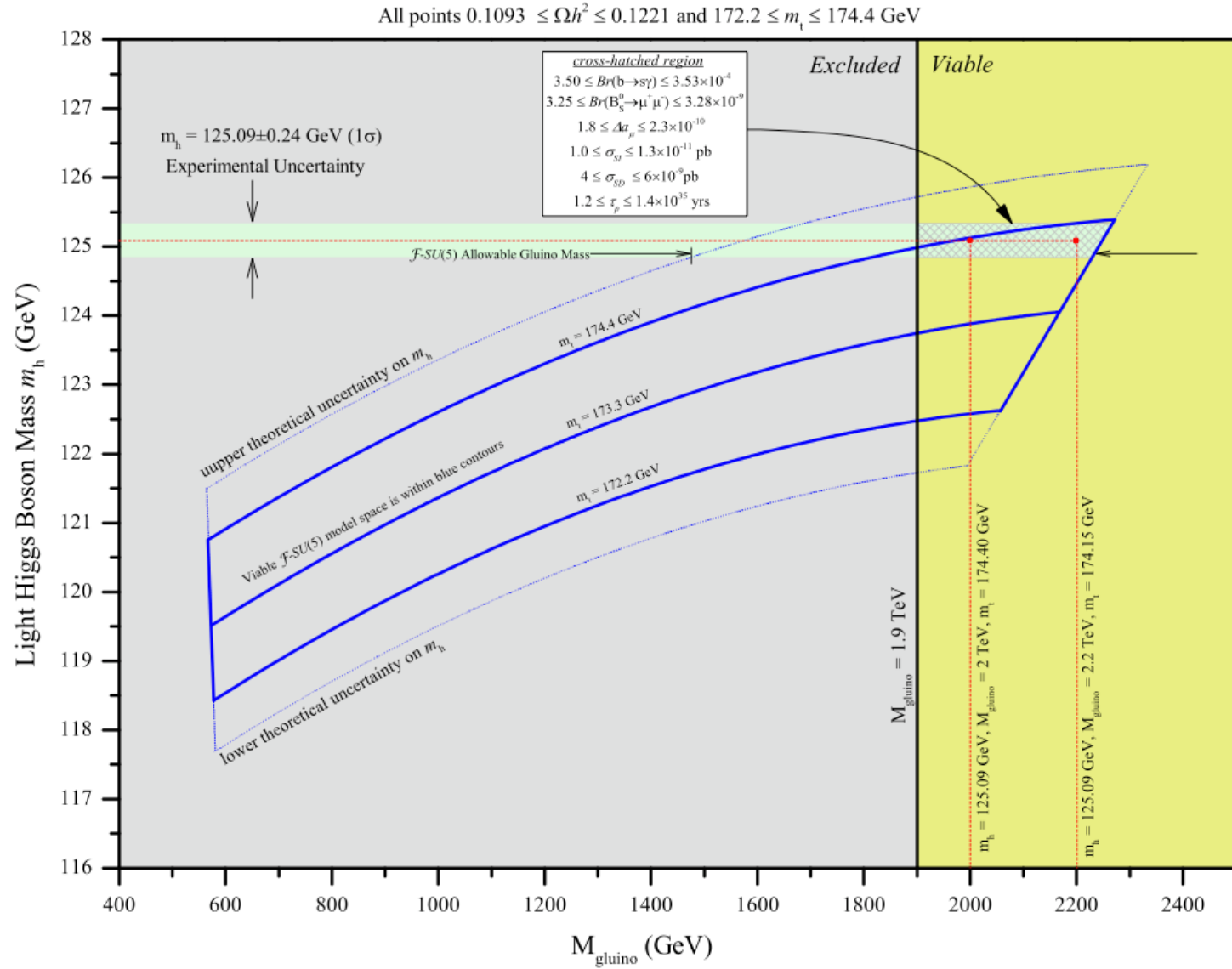
$$\epsilon \simeq -\frac{3}{4\pi} \frac{1}{\left(U_{\nu^c}^\dagger (\lambda_2^D)^2 U_{\nu^c} \right)_{11}} \sum_{i=2,3} \text{Im} \left[\left(U_{\nu^c}^\dagger (\lambda_2^D)^2 U_{\nu^c} \right)_{i1}^2 \right] \frac{m}{M_i}$$

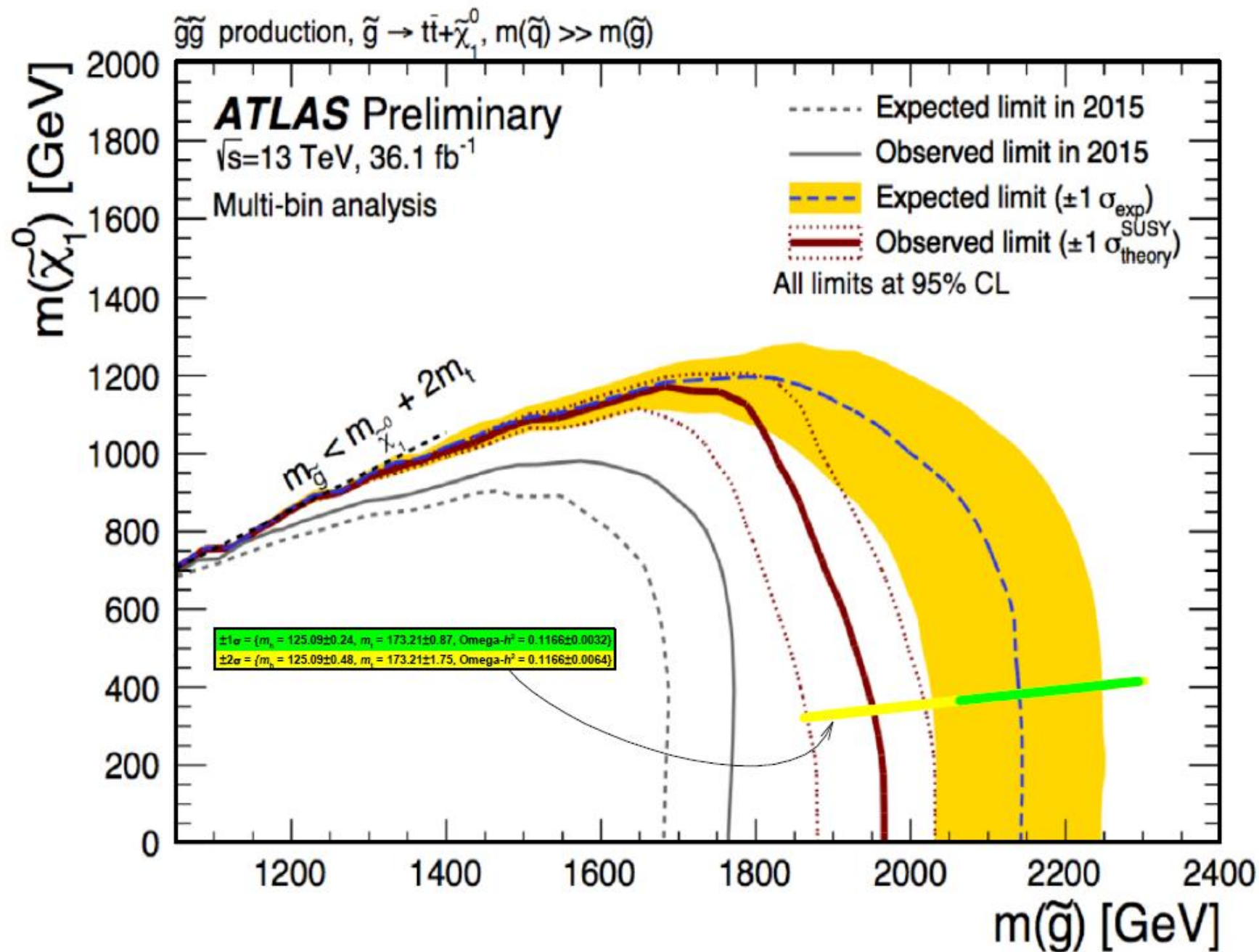
$$\frac{n_B}{s} \simeq 3.8 \times 10^{-11} \delta f \lambda_{1,2,3,7}^2 \lambda_6^{-2} \left(\frac{43/4}{g_{d\Phi}} \right)^{1/4} \left(\frac{915/4}{g_{\text{reh}}} \right)^{1/4} \left(\frac{g_{\text{dec}}}{915/4} \right) \left(\frac{y}{10^{-5}} \right) \times \left(\frac{5 \times 10^{15} \text{ GeV}}{\langle \Phi \rangle} \right)^2 \left(\frac{m_{F,\bar{f},\ell^c,\tilde{\phi}_a}^2 / |m_\Phi|}{10 \text{ TeV}} \right)^{1/2} \left(\frac{m}{3 \times 10^{13} \text{ GeV}} \right)^{1/2}$$

No-Scale Framework for Particle Physics & Dark Matter

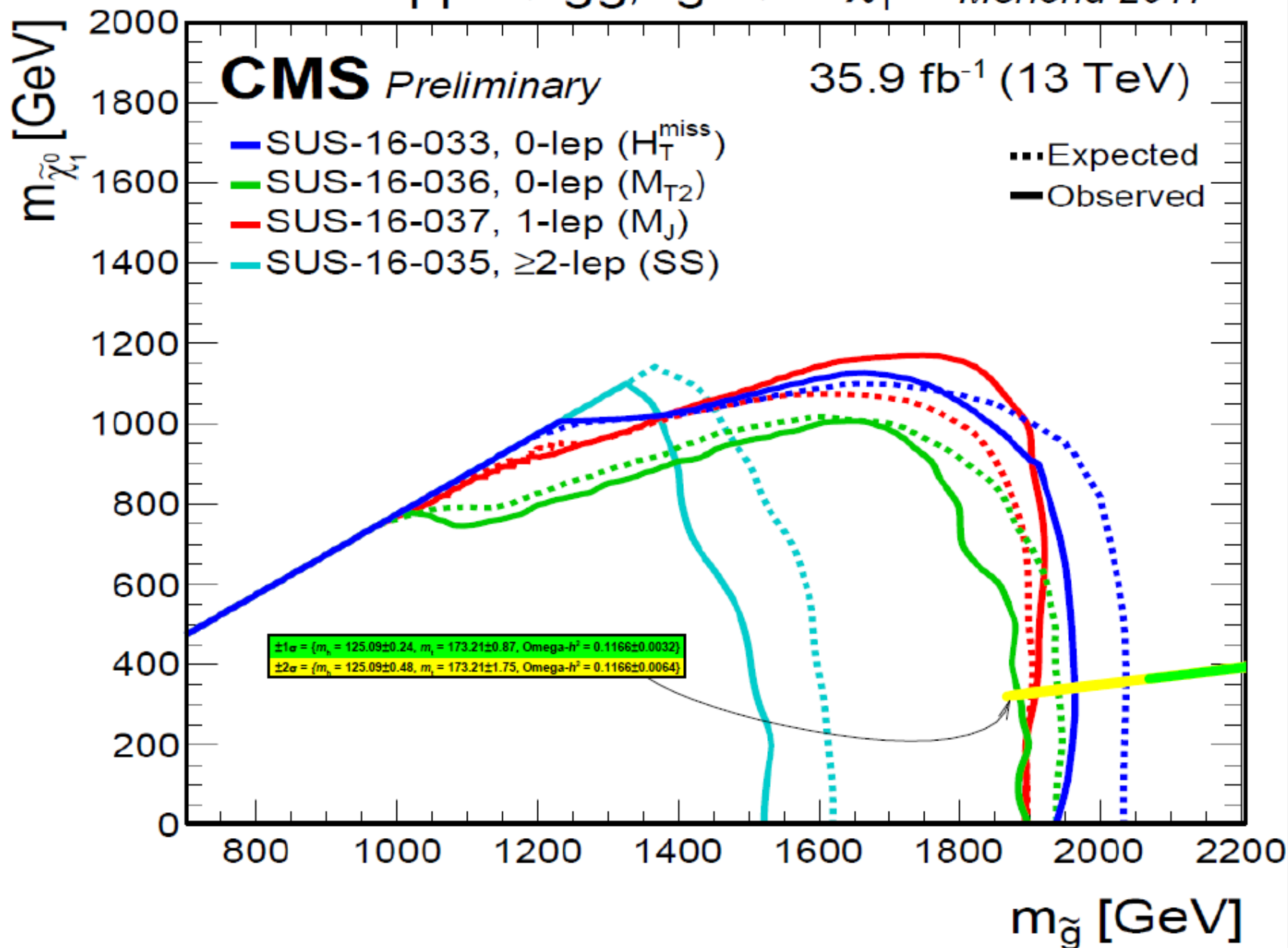
- Incorporating **LHC constraints**, **Higgs mass**, **flavour**, **supersymmetric dark matter**, Starobinsky-like inflation, leptogenesis, neutrino masses, ...







$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t} \tilde{\chi}_1^0$ Moriond 2017



Flipped

Almost

A Model of Everything

Below the Planck Scale

- Starobinsky-like inflation can be embedded within flipped $SU(5) \times U(1)$ model
- Inflaton coupling to neutrinos preferred for baryogenesis – implications for neutrino masses
- Prefer strong reheating after inflation for same reason
- Example how inflation can connect string theory (no-scale supergravity, GUT derived from string) with particle physics accessible to experiment (neutrinos, dark matter, proton decay, LHC, ...)

**THANK YOU
VERY MUCH**

